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13. ABSTRACT *(Maximum 200 words)*
Two (2) moderate preveance cusp electron guns have been purchased from Northrup-Grumman Corporation for a total of $164,726.50. Both of these guns will be used in UCD research programs under the Vacuum Electronics MURI.

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Moderate-Perveance Cusp Electron Gun for High-Efficiency Harmonic Peniotrons

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Moderate-Perveance Cusp Electron Gun for High-Efficiency Harmonic Peniotrons

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Moderate-Perveance Cusp Electron Gun for High-Efficiency Harmonic Peniotrons

1. Overview

A novel electron gun has been ordered from the Northrop Grumman Corp. This gun will be employed in the UC Davis gyro-device program to drive highly efficient harmonic peniotrons. Although gyrotrons are currently the primary source of high power at millimeter-wave frequencies, producing continuous megawatt power levels at frequencies as high as 140 GHz with an efficiency of roughly 40%; a recent experiment at Tohoku University [1] has demonstrated that peniotrons are capable of significantly higher efficiency. The peniotron has been known for almost twenty years to potentially be capable of nearly complete electron energy transfer to wave energy [2-7]. However, peniotrons are usually dominated by competing gyrotron interactions, so that the peniotron is suppressed before it can reach saturation [8]. Previous peniotron experiments have only hinted at their potential. It is therefore necessary to consider competing gyrotron modes when designing a peniotron. The Cusp electron that has been ordered produces an axis-encircling electron beam that is selective about which modes with which it is resonant.

The moderate perveance Cusp gun, which produces a 70 kV, 8 A, axis-encircling electron beam, will initially be used to drive a second harmonic peniotron [9] that has been designed for high efficiency and relative immunity to mode competition from gyrotron interactions. To ensure stability from competing gyrotron interactions, the peniotron will operate in the lowest order mode of a slotted four-vane circuit shown in Fig.1, the $\pi/2$ mode. The cavity is strongly diffraction coupled for high circuit efficiency. The 33 GHz, slotted second-harmonic peniotron is predicted to yield 300 kW with an electron efficiency of 58% and a device efficiency of 52%. The device is currently being constructed at UC Davis and will be driven by the moderate perveance electron cusp gun developed by Northrop Grumman.

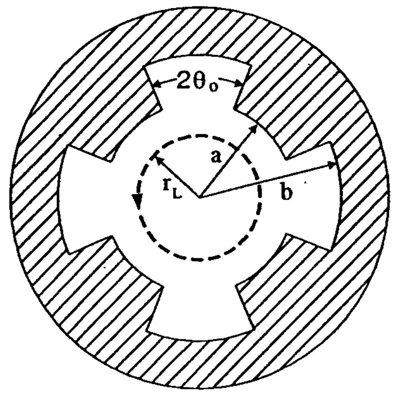

Fig. 1. ***Cross-section of an axis-encircling electron beam within a slotted cavity with four vanes.***

2. Highly Efficient Peniotron

Peniotrons have much in common with gyrotrons. They are both fast-wave devices that are driven by the transverse velocity of the electron beam and involve the coupling of cyclotron-resonance modes to the electromagnetic wave. However, the resonance is synchronous in a gyrotron and asynchronous in a peniotron, where synchronous and asynchronous refer to the conditions that the electrons remain in phase with the wave and fall out of phase by 2π in one cyclotron orbit, respectively. The coupled equations for wave growth involve a second-order pole in a gyrotron and a first-order pole in a peniotron, which leads to a different dependence upon cavity length of the start-oscillation current for the gyrotron (L^{-2}) and peniotron (L^{-1}) interactions. In addition, the bunching and saturation mechanisms are completely different in the two devices. In a gyrotron, the electron bunching is due to the relativistic dependence of the cyclotron frequency on energy and occurs in velocity phase space, while in a peniotron, bunching is caused by a non-relativistic $E \times B$ drift. Saturation in a gyrotron is usually due to trapping, but peniotrons are not limited by trapping, which accounts for their higher potential efficiency. In a peniotron with an ideal electron beam without velocity spread or guiding center spread, all electrons follow the same trajectory, except that the orbits are rotated in azimuth as a function of the RF phase, and all electrons transfer most of their energy to the wave.

Under certain circumstances, the peniotron interaction will be dominant. The recent successful peniotron experiment at Tohoku University achieved an electron efficiency of 70% at the third harmonic [1]. An axis-encircling electron beam interacted with the fourth-order azimuthal ($m = 4$) component of the 2π mode in a four-vane slotted circuit. However, since only 50% of the generated RF power was coupled out of the critically coupled cavity, the device efficiency was a more modest 35%. In order to achieve high device efficiency, it is necessary to have a high circuit efficiency as well. This necessitates a strongly overcoupled interaction cavity. The objective of the UC Davis peniotron program is to obtain a high device efficiency.

By employing a fast-timescale particle-tracing code [10], a 33 GHz second-harmonic peniotron has been designed to be driven by the moderate perveance Northrop Grumman Cusp electron gun [11] for an overall device efficiency in excess of greater than 50%. In this asynchronous interaction, the axis-encircling electrons can interact at the second-harmonic only with a third-order azimuthal mode. The peniotron will operate in the circularly-polarized $\pi/2$ mode of the four vane circuit shown in Fig. 1, whose dominant azimuthal harmonics are $m = 1$ and $m = 3$. By bundling the desired $m = 3$ mode with an $m = 1$ mode, the operating mode is then the lowest order mode of the circuit. The power curve for the slotted second-harmonic peniotron described in Table I is shown in Fig. 2. For a 70 kV, 8 A electron beam with $v_{\perp}/v_z = 1.5$, $\Delta v_z/v_z = 0.1$ and $\Delta r_c/r_L = 0.1$, the peniotron is predicted to produce 300 kW with an electron beam conversion efficiency of 58% and a device efficiency of 52%.

Table I. Parameters for the slotted 33 GHz second-harmonic peniotron.

Beam Voltage	70 kV
Beam Current	8 A
Velocity Ratio, $v_{\perp}/v_z$	1.5
Velocity Spread, $\Delta v_z/v_z$	10%
Guiding Center Spread, $\Delta r_c/r_L$	10%
Magnetic Field	6.5 kG
Number of Vanes	4
Mode	$\pi/2$
Axial Mode Number, m	1
Electron-Vane Ratio, r_L/a	0.65
Vane Depth, b/a	1.45
Inner Vane Radius, a	0.182 cm
Cavity Length	3.1 cm
Unloaded Q, Q_o	3500
Loaded Q, Q_L	375
Efficiency, Electron	58%
Efficiency, Device	52%

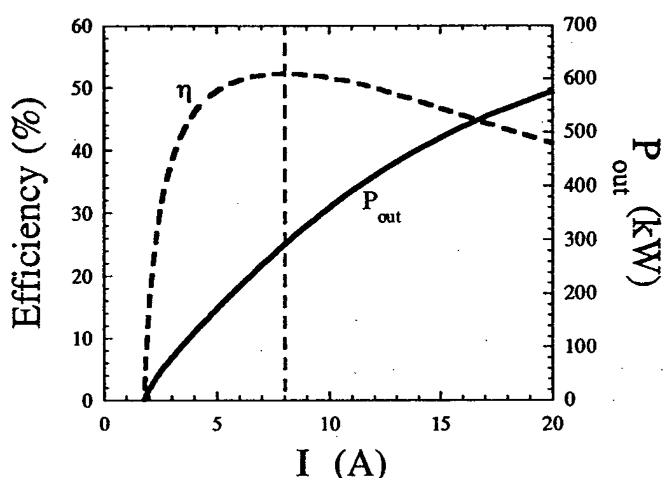

Fig. 2. ***Dependence of the output power (unbroken curve) and device efficiency (broken curve) on the electron beam current in the slotted second-harmonic peniotron [Table I].***

3. Cusp Axis-Encircling Electron Gun

A Cusp electron gun [11] developed and built by Northrop Grumman will be used to produce the axis-encircling beam for the peniotron. The gun employs a convergent Pierce gun with a spherical annular cathode. The initially axial electron beam starts to spin due to the $\mathbf{v_z} \times \mathbf{B_r}$ force in the magnetic field reversal region. The design parameters for the gun are 70 kV, 8 A and $v_\perp/v_z = 1.5$. One of the interesting features of the field reversal gun is that there is a dependence of $v_\perp/v_z$ on well defined parameters that can be predicted using Busch's theorem [12] which simply states that the canonical angular momentum of an electron is conserved. Therefore, the transverse velocity changes axially with varying magnetic field. The general form of Busch's Theorem can be written as

$$\dot{\theta} = \frac{\eta}{2\gamma c}\left[B_z - B_{zo}\frac{r_o^2}{r^2}\right] \tag{1}$$

where $\dot{\theta}$ is the angular velocity, η is the charge to mass ratio of an electron, γ is the relativistic factor, and B_{zo} and r_o are the axial magnetic field amplitude and the radius where the angular velocity is zero. For the Cusp gun, B_{zo} is the axial field amplitude at the cathode, r_o is the cathode radius, B_z and r are, respectively, the flux axial magnetic field and Larmor radius (r_L) at the position in the circuit where $v_\perp/v_z$ is being evaluated. Busch's theorem applied to the Cusp gun can then be written as

$$\frac{v_\perp}{r_L} = \frac{\eta}{2\gamma c}\left[B_{circ} - B_{cath}\frac{r_{cath}^2}{r_L^{\,2}}\right]. \tag{2}$$

Substituting

$$r_L = \frac{v_\perp \gamma c}{\eta B_{circ}} \quad \text{and} \quad v_\perp = v\sqrt{\frac{\alpha^2}{1+\alpha^2}}$$

into Eq. (2) and solving for α, where $\alpha = v_\perp/v_z$, gives

$$\alpha = \sqrt{\frac{-r_o^2\eta^2 B_{cath} B_{circ}}{\gamma^2 v^2 c^2 + r_{cath}^2 \eta^2 B_{cath} B_{circ}}} \tag{3}$$

Furthermore, rewriting B_{cath} and B_{circ} in terms of the relativistic cyclotron frequency, Eq. (3) simplifies to the convenient form

$$\alpha = \frac{v_\perp}{v_z} = \sqrt{\frac{-r_{cath}^2 \Omega_{cath} \Omega_{circ}}{v^2 + r_{cath}^2 \Omega_{cath} \Omega_{circ}}} \tag{4}$$

where Ω_{cath} is the relativistic cyclotron frequency at the cathode and Ω_{circ} is the relativistic cyclotron in the circuit at the position where $v_\perp/v_z$ is being evaluated. The figure of merit determining the final electron transverse velocity was found to be $r_{cath}{}^2\Omega_{cath}\Omega_{circ}/v^2$. Extremely high values of $v_\perp/v_z$ can be achieved when this term approaches negative unity. Once the beam voltage, circuit magnetic field and cathode radius have been chosen, the beam's $v_\perp/v_z$ is controlled by changing the reversed magnetic field amplitude at the cathode. Figures 3 and 4 show the behavior of the beam's α for the Northrop Grumman Cusp gun from Eq. (4). Each parameter has a critical value at which the electrons reflect.

The theoretical dependence of α on B_{cath} for the Northrop Grumman Cusp gun was compared to the results obtained from EGUN [13] electron trajectory simulations and measurement [11]. The results are shown in Fig. 5. There is reasonably good agreement near the design α of the gun where the beam ripple and velocity spread are low. However, the values diverge away from the Cusp gun's design value for α because the beam ripple and velocity spread increases and this is not accounted for in the theory described above.

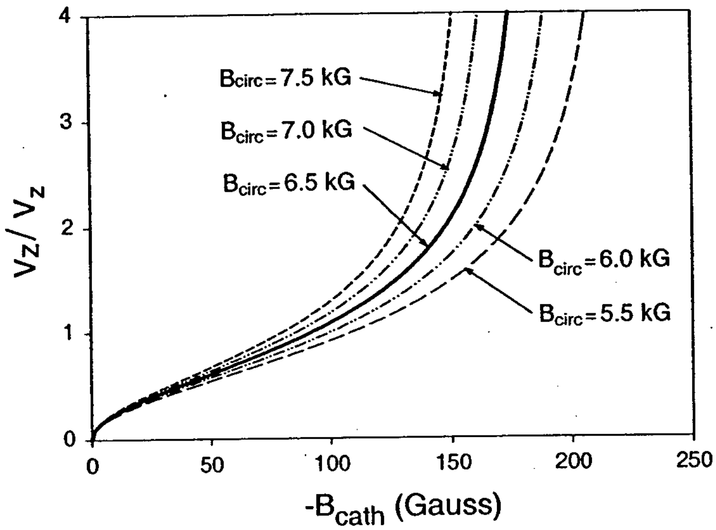

Fig. 3. *Dependence of the final $v_\perp/v_z$ on the magnetic field at the cathode for various values of magnetic field in the circuit for the Northrop Grumman Cusp gun from analytic theory (Eq. 4) [70 kV, r_{cath}(mean) = 0.841 cm].*

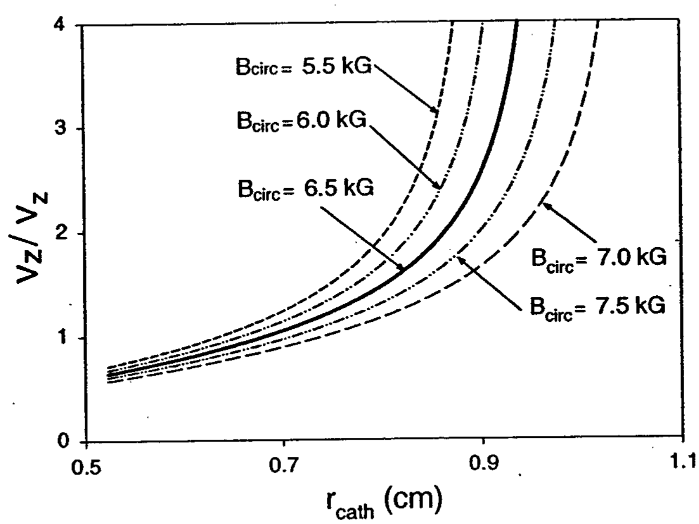

Fig. 4. *Dependence of the final $v_\perp/v_z$ on the cathode radius for various values of magnetic field in the circuit for the Northrop Grumman Cusp gun from analytic theory (Eq. 4) [70 kV, B_{cath} = -140 G].*

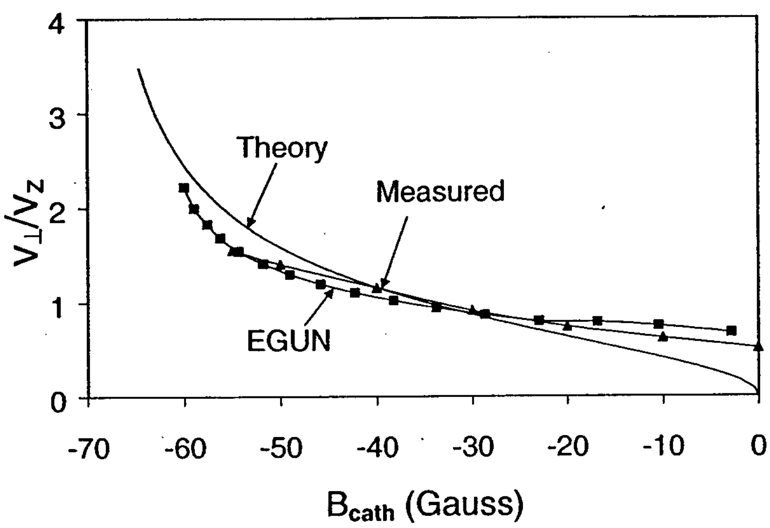

Fig 5. ***Dependence of the final $v_{\perp}/v_z$ on the magnetic field at the cathode from analytic theory (Eq. 4), EGUN simulation, and measurement for the Northrop Grumman Cusp gun [10 kV, r_{cath}(mean) = 0.841 cm, B_{circ} = 2.55 kG].***

4. Acquired Equipment

Two moderate perveance, high power Cusp guns have been ordered from Northrop Grumman Corporation. To minimize the cost, the moderate perveance guns are very similar to the low perveance Cusp guns previously developed under the MURI Program. The new gun design retains the simplicity of the low perveance gun, with the beam velocity spread minimized by a magnetic ring at the cathode (floating pole piece). The specifications of the new gun are listed in Table II. Standard gun processing at NGC includes high potting at full voltage and cathode activation at a reduced voltage. Hot tests at reduced voltage include measuring the current (perveance) as a function of heater current and beam voltage. The order was placed on August 14, 2001 and is described in Table III.

Table II. Parameters of the moderate perveance Cusp gun.

Beam Voltage	70 kV
Beam Current	8 A
Velocity Pitch	1.5
Downstream Magnetic Field	6.5 kG
Maximum Beam Ripple	<0.15
Axial Velocity Spread, $\Delta v_z/v_z$	<10%

Table III. Purchase information

Item	Quantity	Description	Unit Price	Total Price
1	2	Moderate Perveance Cusp Gun	$76,975.00	$153,950.00
			Item Subtotal:	$153,950.00
			Tax Subtotal:	$10,776.50
			Grand Total:	$164,7265.50

5. References

[1] T. Ishihara, K. Sagae, N. Sato, H. Shimawaki, and K. Yokoo, "Highly Efficient Operation of Space Harmonic Peniotron at Cyclotron Harmonics," *IEEE Trans. on Electron Devices,* vol. 46, no. 4, pp. 798-802, 1999.

[2] K. Yamanouchi, S. Ono, and Y. Shibata, "Cyclotron Fast Wave Tube: The Double Ridged Travelling Wave Peniotron," *Proc. Of 5th Int. Congress on Microwave Tubes (Paris)*, pp. 91-102, 1964.

[3] G. Dohler, D. Gallagher, and R. Moats, "The Peniotron: A Fast Wave Device for Efficient High-Power mm-Wave Generation," *Tech. Dig. of IEEE IEDM*, pp. 400-403, 1978.

[4] S.P. Kuznetsov, D.I. Trubetskov, and A.P. Chetverikov, "Nonlinear Analytical Theory of the Peniotron," *Sov. Tech. Phys. Lett.*, vol. 6, no. 10, pp. 498-499, 1980.

[5] G. Dohler, "Peniotron Interactions in Gyrotrons II. Quantitative Analysis," *Int. J. of Electron.*, vol. 56, no. 5, pp. 629-640, 1984.

[6] S. Ono, K. Tsutaki, and T. Kageynama, "Proposing the Gyro-Peniotron with Its Operation Analysis," *Tech. Dig. of IEEE IEDM,* pp. 456-459, 1983

[7] P. Vitello, "Cyclotron Maser and Peniotron-Like Interactions in a Whispering Gallery Mode Gyrotron," *IEEE Trans. on MTT*, vol. 32, no. 8, pp. 917-921, 1984.

[8] P. Vitello and K. Ko, "Mode Competition in the Gyro-Peniotron Oscillator," *IEEE Trans. on Plasma Sci.*, vol. 13, no. 6, pp. 454-463, 1985.

[9] D.B. McDermott, Y. Hirata, L.J. Dressman, D.A. Gallagher and N.C. Luhmann, Jr., "Efficient Ka-Band Second-Harmonic Slotted Peniotron," *IEEE Trans. on Plasma Science*, vol. 28, no. 3, p. 953-958, 2000.

[10] K.R. Chu, M.E. Read, and A.K. Ganguly, "Methods of Efficiency Enhancement and Scaling for the Gyrotron Oscillator," *IEEE Trans. on MTT.,* vol. 28, no. 4, pp. 318-325, 1980.

[11] D. A. Gallagher, M. Barsanti, F. Scafuri, and C. Armstrong, "High-power cusp-gun for harmonic gyro-device applications", *IEEE Trans. Plasma Sci.*, vol. 28, pp. 695-699, 2000.

[12] H. Busch, "Berechnung der bahn von kathodenstrahlen im axialsymmetrischen elektromagnetischen felde," *Z. Phys.*, vol. 81, pp. 974-993, 1926.

[13] W. D. Herrmannsfeldt, "EGUN – Electron optics and gun design program," Technical Report 331, SLAC, 1988.